

A new formulation of the Type Ia SN rate and its consequences on galactic chemical evolution

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ABSTRACT

In recent papers Mannucci et al. (2005, 2006) suggested, on the basis of observational arguments, that there is a bimodal distribution of delay times for the explosion of Type Ia SNe. In particular, a percentage from 35 to 50% of the total Type Ia SNe should be composed by systems with lifetimes as short as 10^8 years, whereas the rest should arise from smaller mass progenitors with a much broader distribution of lifetimes. In this paper, we test this hypothesis in models of chemical evolution of galaxies of different morphological type: ellipticals, spirals and irregulars. We show that this proposed scenario is compatible also with the main chemical properties of galaxies. In this new formulation, we simply assume that Type Ia SNe are originating from C-O white dwarfs in binary systems without specifying if the progenitor model is the single-degenerate or the double degenerate one or a mixture of both. In the framework of the single degenerate model, such a bimodal distribution of the time delays could be explained if the binary systems with a unitary mass ratio are favored in the mass range $5\text{--}8M_{\odot}$, whereas for masses $< 5M_{\odot}$ the favored systems should have the mass of the primary much larger than the mass of the secondary. When the new rate is introduced in the two-infall model for the Milky Way, the derived Type Ia SN rate as a function of cosmic time shows a high and broad peak at very early epochs thus influencing the chemical evolution of the galactic halo more than in the previous widely adopted formulations for the SNIa rate (for example Greggio & Renzini, 1983). As a consequence of this, the [O/Fe] ratio decreases faster for [Fe/H] > -2.0 dex, relative to the old models. For a typical elliptical of $10^{11}M_{\odot}$ of luminous mass, the new rate produces average $[\alpha/\text{Fe}]$ ratios in the dominant stellar population still in agreement with observations. The Type Ia SN rate also in this case shows an earlier peak and a subsequent faster decline relative to the previous results, but the differences are smaller than in the case of our Galaxy. We have also checked the effects of the new Type Ia SN rate on the evolution of the Fe content in the ICM, as a consequence of its production from cluster ellipticals and we found that less Fe in the ICM is produced with the new rate, due to the higher fraction of Fe synthesized at early times and remaining locked into the stars in ellipticals. For dwarf irregular galaxies suffering few bursts of star formation we obtain [O/Fe] ratios larger by 0.2 dex relative to the previous models.

Key words: galaxies: abundances – galaxies: evolution – supernovae: general

1 INTRODUCTION

The Type Ia supernova (SN) rate is a fundamental ingredient in models of galactic evolution. In the pioneering work of Greggio & Renzini (1983a, hereafter GR83) there was,

for the first time, an expression for the Type Ia SN rate in the scenario of the single degenerate model. In this scenario, SNe Type Ia arise from the explosion of a C-O white dwarf in a close binary system where the companion is ei-

ther a red giant or a main sequence star (Whelan & Iben, 1973; Munari & Renzini, 1992; Kenyon et al. 1993; Hachisu et al., 1996; 1999). An alternative model for progenitors of Type Ia SNe was proposed by Iben & Tutukov (1984). In this scenario two C-O white dwarfs of $\sim 0.7M_{\odot}$ merge after loss of angular momentum due to gravitational wave emission, and explode since the final object reaches the Chandrasekhar mass. Tornambé & Matteucci (1986) formulated a Type Ia SN rate in this scenario and applied it to galactic chemical evolution models. In the following, Matteucci & Greggio (1986) tested the GR83 rate by means of a detailed chemical evolution of the Milky Way and interpreted the $[\alpha/\text{Fe}]$ ratios versus $[\text{Fe}/\text{H}]$ as due to the delay in the Fe production from Type Ia SNe, thus confirming previous suggestions (Tinsley, 1979; Greggio & Renzini 1983b). They suggested that the time scale for the change in the slope of this relation, due to the Fe restored in a substantial amount by Type Ia SNe is $\sim 1 - 1.5$ Gyr. This timescale is not universal but related to the specific history of star formation in galaxies, as shown by Matteucci & Recchi (2001, hereafter MR01), being shorter than in the solar neighbourhood for ellipticals and longer for irregular systems. The formulation of the SNIa rate in the single degenerate scenario was later implemented by Greggio (1996), who considered also the possibility of sub-Chandrasekhar masses. In the single degenerate scenario the clock for the explosion is given by the lifetime of the secondary mass which transfers material over the primary star when it fills its Roche lobe. In the original formulation of GR83 and in the one of MR01 the mass range for the progenitors of both the primary and secondary masses is $0.8-8M_{\odot}$. The upper limit is given by the fact that stars with masses $M > 8M_{\odot}$ ignite carbon in a non degenerate core and therefore do not end their lives as C-O white dwarfs. The lower limit is instead obviously due to the fact that we are only interested in systems which can produce a Type Ia SN in a Hubble time. In this scenario the very first binary system exploding as a Type Ia SN is made of two stars of $8M_{\odot}$ and therefore it occurs only 30-40 Myr since the beginning of star formation.

Recently, Mannucci et al. (2005) showed that two populations of progenitors of Type Ia SNe are needed to explain the dependence of the rates on the colors of the parent galaxy. The presence of Type Ia SNe in old, red, quiescent galaxies is an indication that part of these SNe originate from old stellar populations. On the contrary, the increase of the rate in blue galaxies (by a factor of 30 going from (B-K) ~ 2 to (B-K) ~ 4.5) shows that part of the SN Ia progenitors is related to young stars and closely follows the evolution of the star formation rate. Mannucci, Della Valle & Panagia (2006, hereafter MVP06), on the basis of the previously described relation between the Type Ia SN rate and the color of the parent galaxies, their radio power as measured by Della Valle et al. (2005), and cosmic age, concluded that there are two populations of progenitors of Type Ia SNe. They have demonstrated that the current observations can be accounted for only if about half of the SNe Ia (*prompt SNe Ia*) explode within 10^8 years after the formation of their progenitors, while the rest explode during a wide period of time extending up to 10 Gyrs (*tardy SNe Ia*). As already mentioned, the GR83 rate in its original formulation contains a population of Type Ia SNe exploding rapidly, at variance with other progenitor models suggested in the literature such

as that of Kobayashi et al. (1998), where the maximum mass for the secondary stars is assumed to be $2.6 M_{\odot}$ and therefore has a delay time distribution function (hereafter DTD), namely the distribution of the explosion times, quite different from the one of GR83. In general, no Type Ia SN rate proposed in the literature up to now (GR83, Yungelson & Livio, 2000; MR01, Belczynsky et al 2005; Greggio 2005), both in the framework of single and double-degenerate scenarios, can reproduce the bimodality of the DTD derived by MVP06. In fact, although some of these models (GR83 and MR01, single degenerate; Greggio 2005, double degenerate) predict a DTD in agreement with the evolution of the SNIa rate with redshift and with galaxy color, none of them predicts enough SNIa within the first 10^8 years to fully account for the radio dependence of the rate in ellipticals.

The aim of this paper is to adopt this new DTD in models of chemical evolution of galaxies (ellipticals, spirals and irregulars). In particular, we will calculate the Type Ia SN rate in different galaxies by adopting different star formation rates, then we will compare the chemical evolution results obtained with this new rate with the observations and with the results of previous models adopting the formulation of the Type Ia SN rate of MR01. Scannapieco & Bildsten (2005) used the results of Mannucci et al. (2005) to derive, in the framework of a simple closed-box model, the evolution of the SN Ia rate and the chemical evolution of the Milky Way, as well as the evolution of the Fe content in the intracluster medium.

Here, we will apply the new Type Ia rate formulation to very detailed chemical evolution models for galaxies of different morphological type, taking into account both infall and outflow and already reproducing the majority of observational constraints.

The paper is organized as follows: in Section 2 the formulations for the SNIa rate of GR83 and MR01 together with the new one are presented. In Section 3 the galactic chemical evolution models are discussed and in Section 4 the model results are shown and compared to each others and with data. Finally, in Section 5 some conclusions are drawn.

2 TYPE IA SUPERNOVAE

2.1 Progenitors

We recall here the most common models for the progenitors of Type Ia SNe proposed insofar:

- The merging of two C-O white dwarfs (WDs), due to gravitational wave radiation, which reach the Chandrasekhar mass and explode by C-deflagration (Iben and Tutukov 1984). This is known as double-degenerate (DD) scenario. The progenitor masses should be in the range $5-9M_{\odot}$ to ensure two WDs of $\sim 0.7M_{\odot}$ in order to reach the Chandrasekhar mass. Moreover the mass of the primary should be almost equal to the mass of the secondary. The clock for the explosion in this scenario is given by the lifetime of the secondary plus the gravitational time delay (Matteucci & Tornambé 1986).
- The C-deflagration of a Chandrasekhar mass ($\sim 1.4M_{\odot}$) C-O WD after accretion from a non-degenerate companion (Whelan and Iben 1973; Munari and Renzini

1992; Kenyon et al. 1993). This model is known as the single-degenerate (SD) one. The main problem with this scenario is the narrow range of permitted values of the mass accretion rate in order to obtain a stable accretion, instead of an unstable accretion with a consequent nova explosion and mass loss. In this case, in fact, the WD never achieves the Chandrasekhar mass. In particular, Nomoto, Thielemann & Yokoi (1984) found that a central carbon-deflagration of a WD results for a high accretion rate ($\dot{M} > 4 \cdot 10^{-8} M_{\odot} \text{ yr}^{-1}$) from the secondary to the primary star (the WD). They found that $\sim 0.6 - 0.7 M_{\odot}$ of Fe plus traces of elements from C to Si are produced in the deflagration, well reproducing the observed spectra. The clock for the explosion here is given by the lifetime of the secondary star.

- A sub-Chandrasekhar C-O WD exploding by He-detonation induced by accretion of He-rich material from a He star companion (Limongi and Tornambé 1991).

- A more recent model by Hachisu et al. (1996; 1999) is based on the classical scenario of Whelan and Iben (1973) (namely C-deflagration in a WD reaching the Chandrasekhar mass after accreting material from a star which fills its Roche lobe), but they find an important metallicity effect. When the accretion process begins, the primary star (WD) develops an optically thick wind which helps in stabilizing the mass transfer process. When the metallicity is low ($[Fe/H] < -1$), the stellar wind is too weak and the explosion cannot occur. The clock for the explosion here is also given by the lifetime of the secondary star plus the chemical evolution delay time, due to the fact that the progenitors of Type Ia SNe do not form before the gas has attained the threshold metallicity.

2.2 The formulation of the SNIa rate of GR83 and MR01

In the formulation of the Type Ia rate by GR83, based on the Whelan and Iben (1973) model, the explosion times correspond to the lifetimes of stars in the mass range $0.8 - 8 M_{\odot}$. In fact, the maximum initial mass which leads to the formation of a C-O WD is $\sim 8 M_{\odot}$, although stellar models with overshooting predict a lower value (e.g. Marigo et al. 1996), which means that the first system, made of two $8 M_{\odot}$ stars, explodes after $\sim 3 - 4 \cdot 10^7$ years from the beginning of star formation. The minimum total mass of the binary system is assumed to be $3 M_{\odot}$, to ensure that the WD and the companion are large enough to allow the WD with the minimum possible mass ($\sim 0.5 M_{\odot}$) to reach the Chandrasekhar mass limit after accretion. The smallest possible secondary mass is $0.8 M_{\odot}$ and therefore the maximum explosion time is the age of the universe. This ensures that this model is able to predict a present time SN Ia rate for those galaxies where star formation must have stopped several Gyr ago, such as ellipticals.

In this formalism the SNIa rate for an instantaneous starburst, in other words the DTD function, can be written as:

$$R_{\text{Ia}}(t) = A \int_{M_{\text{B,inf}}}^{M_{\text{B,sup}}} \phi(M_{\text{B}}) f\left(\frac{M_2(t)}{M_{\text{B}}}\right) \frac{dM_{\text{B}}}{M_{\text{B}}}, \quad (1)$$

where $M_{\text{B}} = M_1 + M_2$ is the total mass of the binary system, with M_1 being the primary stars (the originally most

massive one) and M_2 being the secondary star, $M_{\text{B,inf}}$ and $M_{\text{B,sup}}$ are the minimum and maximum masses for the binary systems contributing at the time t . The maximum value that M_{B} can assume is called M_{BM} and the minimum M_{Bm} . These values (maximum and minimum mass of the binary systems able to produce a SNIa explosion) are model-dependent. In particular, GR83 considered that only stars with $M \leq 8 M_{\odot}$ could develop a degenerate C-O core, thus obtaining an upper limit $M_{\text{BM}} = 16 M_{\odot}$ for the mass of the binary system. The adopted lower limit is $M_{\text{Bm}} = 3 M_{\odot}$, as discussed previously. The constant A represents a free parameter which indicates the fraction of binary systems of the type necessary to produce Type Ia SNe relative to all the stars in the mass range $3-16 M_{\odot}$. This parameter is fixed by reproducing the present time SN Ia rate.

The extremes of the integral (1) are functions of time and for a fixed time t , are:

$$M_{\text{B,inf}} = \max(2M_2(t), M_{\text{Bm}}) \quad (2)$$

$$M_{\text{B,sup}} = \frac{1}{2} M_{\text{BM}} + M_2(t), \quad (3)$$

where $M_{\text{B,sup}} = M_{\text{BM}}$ when $M_2(t) = 8 M_{\odot}$.

We define $\mu = M_2/M_{\text{B}}$ as the mass fraction of the secondary and $f(\mu)$ is the distribution function of this ratio. Statistical studies (e.g. Tutukov & Yungelson 1980) indicates that mass ratios close to one are preferred, so the formula:

$$f(\mu) = 2^{1+\gamma} (1 + \gamma) \mu^{\gamma}, \quad (4)$$

is commonly adopted, with $\gamma=2$ as a parameter.

The function $\phi(M_{\text{B}})$ is the initial mass function (IMF) and has the form:

$$\phi(M_{\text{B}}) = C M_{\text{B}}^{-(1+x)} \quad (5)$$

where x is the so-called Salpeter (1955) index, the IMF is defined in the mass interval $0.1-100 M_{\odot}$, and C is the normalization constant (see eq. 12). The IMF that we will use will be either the Salpeter one with $x=1.35$ all over the mass range or a multi-slope IMF as suggested by Scalo (1986).

In order to compute the Type Ia SN rate we need to convolve the DTD function described above with a suitable star formation rate.

In particular:

$$R_{\text{Ia}}(t) = A \int_{M_{\text{B,inf}}}^{M_{\text{B,sup}}} \phi(M_{\text{B}}) \int_{\mu_{\text{min}}}^{\mu_{\text{max}}} f(\mu) \psi(t - \tau_{M_2}) d\mu dM_{\text{B}}, \quad (6)$$

The star formation rate in this case has to be evaluated at the time $(t - \tau_{M_2})$, with τ_{M_2} being the lifetime of the secondary star and the clock for the explosion. The star formation rate (SFR) $\psi(t)$ will be chosen according to the morphological type of the galaxies we will consider.

In Figure 1 we show the normalized DTD from MR01. It represents the results of eq. (1), namely the Type Ia SN rate computed under the scenario of the single-degenerate for an instantaneous burst. The assumed IMF is the one-slope Salpeter (1955) one.

2.3 The new formulation of the Type Ia SN rate

In Figure 2 we show the normalized DTD of MVP06. We have approximated this DTD with the following expressions:

$$\log DTD(t) = 1.4 - 50(\log t - 7.7)^2 \quad (7)$$

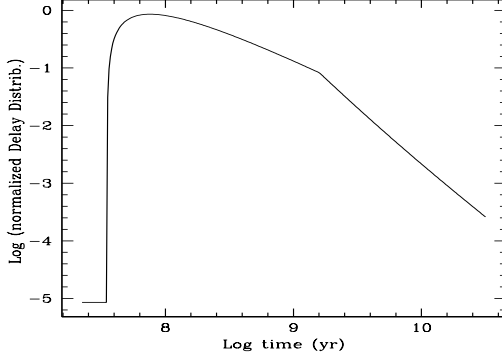


Figure 1. The normalized time delay distribution function (DTD) as obtained from eq. (1) according to MR01.

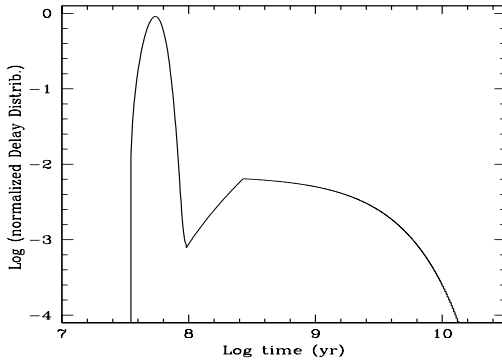


Figure 2. The normalized time delay distribution function (DTD) as proposed by MVP06.

for $t < 10^{7.93}$ yr, and

$$\log DTD(t) = -0.8 - 0.9(\log t - 8.7)^2 \quad (8)$$

for $t > 10^{7.93}$ yr, where the time is expressed in years.

It is worth noting that, in order to simplify the comparison, we have imposed that the number of SNe Ia in the MR01 formulation (i.e. the integral of the rate in Figure 1) be the same as the number of SNe Ia obtained from Figure 2 with the DTD of MVP06.

This new formulation, being analytical, is easier to implement in a galactic chemical evolution code, since the Type Ia SN rate for any history of star formation can be derived, by following the formalism developed by Greggio (2005) we can write:

$$R_{Ia}(t) = k_\alpha \int_{\tau_i}^{\min(t, \tau_x)} A(t - \tau) \psi(t - \tau) DTD(\tau) d\tau \quad (9)$$

where $A(t - \tau)$ is the fraction of binary systems which give rise to Type Ia SNe, in analogy with eq. (1) and in principle it can vary in time. Here we will assume it constant. It is worth noting that the fraction A in this new formulation has a different meaning than in the old one. In particular, in the new formulation is the fraction of binary systems with those particular characteristics to give rise to Type Ia SNe relative to the whole range of star masses ($0.1\text{--}100M_\odot$) not only relative to the mass range $3\text{--}16M_\odot$ as it is in MR01.

The time τ is the delay time defined in the range (τ_i, τ_x) so that:

$$\int_{\tau_i}^{\tau_x} DTD(\tau) d\tau = 1 \quad (10)$$

where τ_i is the minimum delay time for the occurrence of Type Ia SNe, in other words the time at which the first SNe Ia start occurring. We assume, for this new formulation of the SN rate that τ_i is the lifetime of a $8M_\odot$, while for τ_x , which is the maximum delay time, we assume the lifetime of a $0.8M_\odot$, exactly as in the single degenerate scenario described before.

Finally, k_α is the number of stars per unit mass in a stellar generation and contains the IMF.

In particular:

$$k_\alpha = \int_{m_L}^{m_U} \phi(m) dm \quad (11)$$

where $m_L = 0.1M_\odot$ and $m_U = 100M_\odot$ and define the whole range of existence of the stars.

The normalization condition for the IMF is the usual one:

$$\int_{m_L}^{m_U} m \phi(m) dm = 1 \quad (12)$$

2.4 Which systems could explain the DTD of MVP06?

A possible justification for this strongly bimodal DTD of MVP06 can be found in the framework of the single degenerate model for the progenitors of Type Ia SNe. In fact, such a DTD can be found if one assumes that the function describing the distribution of mass ratios inside the binary systems, $f(\mu)$, as defined before, is a multi-slope function. In particular, a slope $\mu = 2.0$ should be assumed for systems with stars in the mass range $5\text{--}8M_\odot$, whereas a negative slope ($\mu \sim -0.8/-0.9$) should be adopted for masses lower than $5M_\odot$. This choice means that in the range $5\text{--}8M_\odot$ are preferred the systems where $M_1 \sim M_2$, whereas for lower mass progenitors are favored systems where $M_1 \gg M_2$. However, this expression for $f(\mu)$ should be compared with observational estimates of the mass ratio distribution function. In general, there is not yet an agreement on a universal form for the $f(\mu)$ or the $f(q)$ ($q = \frac{M_2}{M_1}$) function, due to the fact that most stellar samples and observational techniques are affected by observational biases. As already mentioned, Tutukov & Yungelson (1980) suggested a one slope $f(\mu)$ function with $\gamma = 2.0$, whereas Duquennoy and Mayor (1991), from a sample of solar type stars, suggested a one-slope function with a value of $\gamma = -0.35$.

More recently, Kouwenhoven et al. (2005) from A and B type stars in the Scorpius-Centaurus association found a $f(q) = q^{-0.33}$, while Shatsky & Tokovinin (2002), by studying B stars always in the Scorpius-Centaurus association, suggested $f(q) = q^{-0.55}$. Hogeveen (1992) studied the mass ratio distribution of spectroscopic binaries and obtained $f(q) \propto q^{-2}$ for $q > q_0$ with $q_0 = 0.3$ whereas for $q < q_0$ he found a flat distribution. He also estimated that a fraction of 19–45% of the stars in the solar neighbourhood are spectroscopic binaries. Finally, for stars with masses in the range $10\text{--}20M_\odot$, Pinsonneault & Stanek (2006) found

evidence for the existence of two distinct classes of binary systems, each one contributing to about half of the systems: one being characterized by two stars of similar mass and the other by a flat distribution of mass ratios.

In conclusion, the observational situation is still too uncertain to draw firm conclusions and it is better to use the analytical formulation for the DTD, as described before, without worrying about the precise SNIa progenitor model.

Now we can proceed in computing the chemical evolution of galaxies of different morphological type by means of this new formulation of the SNIa rate, as it will be described in the next sections.

3 MODELS OF CHEMICAL EVOLUTION

We describe here the general equations for the chemical evolution of galaxies and the assumptions common to all models. The different morphological types are then identified by the different star formation histories (namely by the SFR, $\psi(t)$; and by the IMF; $\phi(m)$) and by different infall/outflow rates.

The time-evolution of the fractional mass of the element i in the gas within a galaxy, G_i , is described by the basic equation:

$$\dot{G}_i = -\psi(t)X_i(t) + R_i(t) + (\dot{G}_i)_{inf} - (\dot{G}_i)_{out} \quad (13)$$

where $G_i(t) = M_g(t)X_i(t)/M_{tot}$ is the gas mass in the form of an element i normalized to a total fixed mass M_{tot} and $G(t) = M_g(t)/M_{tot}$ is the total fractional mass of gas present in the galaxy at the time t . The quantity $X_i(t) = G_i(t)/G(t)$ represents the abundance by mass of an element i , with the summation over all elements in the gas mixture being equal to unity. $\psi(t)$ is the fractional amount of gas turning into stars per unit time, namely the SFR. $R_i(t)$ represents the returned fraction of matter in the form of an element i that the stars eject into the ISM through stellar winds and supernova explosions; this term contains all the prescriptions concerning the stellar yields and the supernova progenitor models.

The nucleosynthesis prescriptions are common to all models and are taken from: Woosley & Weaver (1995) yields for massive stars (those relative to the solar chemical composition), van den Hoeck & Groenewegen (1997) for low and intermediate mass stars ($0.8 \leq M/M_\odot \leq 8$) and Nomoto et al. (1997) for Type Ia SNe.

The assumed stellar lifetimes for all galaxies are those suggested by Padovani & Matteucci (1993).

The two terms $(\dot{G}_i)_{inf}$ and $(\dot{G}_i)_{out}$ account for the infall of external gas and for galactic winds, respectively. The presence of infall and winds varies for galaxies of different morphological type. Infall is present in all galaxy models but with different timescales, whereas the wind is present in ellipticals and dwarfs but absent in spirals.

The prescription adopted for the star formation history is the main feature which characterizes a particular morphological galactic type.

In its simplest form the SFR, $\psi(t)$, in our models is a Schmidt (1959) law expressed as:

$$\psi(t) = \nu G^k(t) \quad (14)$$

The quantity ν is the efficiency of star formation,

namely the inverse of the typical time-scale for star formation, and is expressed in Gyr^{-1} .

The rate of gas infall is defined as:

$$(\dot{G}_i)_{inf} = C e^{-t/\tau} \quad (15)$$

with C being a suitable constant and τ the infall timescale.

The rate of gas loss via galactic winds for each element i is assumed to be proportional to the star formation rate at the time t :

$$\dot{G}_{iw} = w_i \psi(t) \quad (16)$$

where w_i is a free parameter describing the efficiency of the galactic wind.

In all models the instantaneous recycling approximation is relaxed and the stellar lifetimes are taken into account.

3.1 The Milky Way

The role played by SNe of different Type(II, Ia) in the chemical evolution of the Galaxy has been computed by several authors (Matteucci & Greggio, 1986; Yoshii et al. 1996; Tsujimoto et al. 1995; Chiappini et al. 1997; Kobayashi et al. 1998; Boissier & Prantzos 1999). Here we refer to the model of Chiappini et al. (1997), the so-called two-infall model for the evolution of the Milky Way. A thorough description of this model can be found in Chiappini et al. (1997; 2001; 2003) and François et al. (2004) and we address the reader to these paper for details. It is assumed that the stellar halo formed on a relatively short timescale (1-2 Gyr) by means of a first infall episode, whereas the disk formed much more slowly mainly out of extragalactic gas thanks to a second infall episode. The timescale for the disk formation is assumed to increase with the galactocentric distance ($\tau = 7$ Gyr at the solar circle), thus producing an “inside-out” scenario for the disk formation. The Galactic disk is divided in several rings 2Kpc wide without exchange of matter between them.

The model can follow in detail the evolution of several chemical elements including H, D, He, C,N,O, α -elements, Fe and Fe-peak elements, s- and r-process elements. The IMF is assumed to be constant in space and time and is that of Scalo(1986).

The star formation rate adopted for the Milky Way is a function of both surface gas density and total surface mass density. Such a SFR is proportional to a power $k = 1.5$ of the surface gas density and to a power $h = 0.5$ of the total surface mass density. This formulation of the SFR (details can be found in Chiappini et al. 1997;2001) takes into account the feedback mechanism between stars and gas regulating star formation and is supported by observations (e.g. Dopita and Ryder 1994). In the Milky Way model we also assume a surface density threshold below which the SFR stops, according to Kennicutt (1989;1998). As a consequence of this, the star formation rate goes to zero every time that the gas density decreases below the threshold ($\sim 7M_\odot pc^{-2}$). The efficiency of SF is $\nu = 0.1Gyr^{-1}$ during the disk and $2Gyr^{-1}$ in the halo phase. This model reproduces the majority of the features of the solar vicinity and the whole disk (see Chiappini et al, 1997;2001).

3.2 Elliptical galaxies

For the chemical evolution of ellipticals we adopt the model of Pipino & Matteucci (2004) where we address the reader for details.

Here we recall the main assumptions: ellipticals form by means of a fast collapse of pristine gas where star formation occurs at a very high rate (starburst-like regime), and after a timescale, varying with the galactic mass, each galaxy develops a galactic winds due to the energy deposited by SNe into the interstellar medium (ISM). After the development of this wind no star formation is assumed to take place. The SN feedback is taken into account together with the cooling of SN remnants and the development of galactic winds is calculated in a self-consistent way. Massive but diffuse haloes of dark matter around these galaxies are considered. We assume that the efficiency of star formation rate is higher in more massive objects which evolve faster than less massive ones (inverse-wind scenario, Matteucci, 1994, otherwise called “downsizing”, Cowie et al. 1996). The Salpeter (1955) IMF constant in space and time is adopted. In the SFR expression (eq. 14) we assume $k=1$ and $\nu = 1 - 20\text{Gyr}^{-1}$, going from 10^9 to $10^{12}M_\odot$ of luminous mass. The infall rate is quite fast with a typical $\tau = 0.5\text{Gyr}$. Here we will consider the model corresponding to a typical elliptical of $10^{11}M_\odot$ of luminous mass.

3.3 Dwarf irregulars

For the dwarf irregulars we assume a one zone model with instantaneous and complete mixing of gas inside this zone (see Lanfranchi & Matteucci, 2003). The development of a galactic wind is computed similarly to what is done for ellipticals except that in these small objects the wind does not stop the star formation. The star formation takes place in short bursts of duration not longer than 200 Myr. The star formation rate is again a Schmidt law (eq. 14) with $k = 1$ and $\nu = (0.1 - 0.9)\text{Gyr}^{-1}$. The infall timescale is also quite short ($\tau \sim 0.3 - 0.5\text{Gyr}$) and the IMF is the Salpeter one.

4 MODEL RESULTS

In this section we will show a comparison between results obtained by means of the just described models for different galaxies with the old formulation of the SNIa rate (GR83; MR01) and those obtained with the new rate as described in Section 2.

4.1 The Milky Way

In Figure 3 we report the model results for the Type Ia SN rate as a function of cosmic time in the cases of the old rate (eq. 5) and the new rate (eq. 9). The oscillating behaviour at late times, in both cases, is due to the adoption of a threshold gas density in the SFR. The parameter A , as previously defined, is $A = 0.09$ for the old formulation of the SN Ia rate and for the assumed stellar lifetimes. In fact, if one adopts different stellar lifetimes such as Maeder & Meynet (1989), the value of the parameter is $A = 0.05$ (see Romano et al. 2005 for a detailed discussion). The parameter A indicates the fraction of binary systems producing Type Ia SNe in

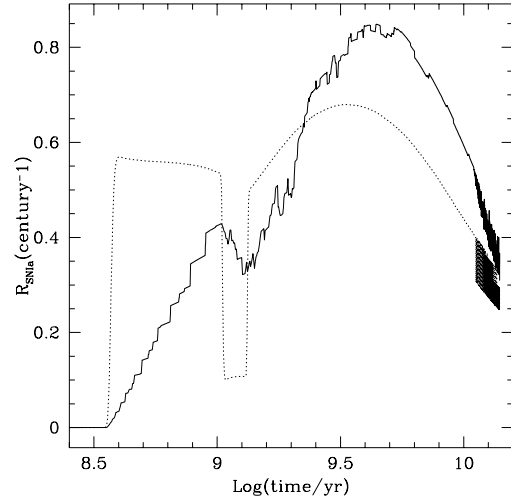


Figure 3. The Type Ia SN rate (expressed in SN Gyr^{-1}) as a function of time in the Milky Way as obtained for the old prescription of the rate (solid curve) and for the new one (dotted curve). The SFR is the same but the DTDs are different, as described in the text. The parameter $A=0.09$ for the MR01 formulation and $A=0.0025$ for the new one (see text). In both cases the IMF is the Scalo (1986) one, which is appropriate for the disk of the Milky Way.

the mass range $3-16M_\odot$ relative to all the stars in this same mass range, and is fixed by reproducing the present time observed Type Ia rate in the Milky Way. The parameter A depends on the assumed stellar lifetimes and IMF. When the new formulation is adopted, this parameter assumes a different meaning, being the fraction of binary systems originating Type Ia SNe relative to whole mass range where the IMF is defined. In particular, for the new rate we have to assume a much lower $A = 0.0025$. One can immediately notice in Figure 3 that the integrals under the two curves are roughly the same whereas the shapes of the curves are quite different. In particular, the old Type Ia SN rate shows a minor peak at around 1 Gyr, then a minimum is reached at ~ 1.4 Gyr and this is the consequence of the gap in the SFR predicted by the two-infall model between the halo-thick-disk and the thin-disk phases. In the new rate the peak at early times is much more pronounced and extended, reflecting the peak in the DTD of MVP06 (prompt Type Ia SNe), then the minimum due to the gap in the SFR is more pronounced than before and it starts at 1 Gyr. The lower values of the new rates after the gap are again a consequence of the assumed DTD. The value of $A=0.0025$ for the new rate is fixed by obtaining a present time rate as close as possible to the observed one ($\sim 0.3 \text{ SNe}(100\text{yr})^{-1}$, Cappellaro et al. 1999) without overestimating the number of SNeIa in the past. In particular, with the new formulation we obtain a present time Type Ia SN rate of $0.25 \text{ SNe}(100\text{yr})^{-1}$, well in agreement with the observed rate inside the observational errors.

At this point, we should check the effects of the new rate on the age-metallicity relation and on $[\text{O}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ relation, shown in Figures 4 and 5, respectively. In Figure 4 we show the plot of the age-metallicity relation as obtained for the solar vicinity. Two cases are shown: the

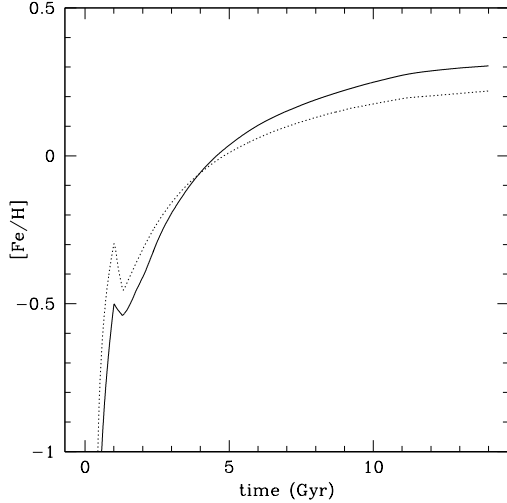


Figure 4. The computed age-metallicity relation in the solar neighbourhood for the old formulation of the DTD (MR01) (continuous line) and the new one (dotted line) with an average Fe per Type Ia SN of $0.7M_{\odot}$. The Fe abundances are normalized to the solar values of Asplund et al. (2005).

results with the old and new Type Ia SN rates. It is worth noting that in the old formulation of Chiappini et al. (1997) it was assumed that each Type Ia SN was producing on average $\sim 0.4M_{\odot}$ of Fe. This was done to take into account the fact that the data indicates that not all Type Ia SNe produce $\sim 0.6 - 0.7M_{\odot}$ of Fe but that there is a certain spread. This lower Fe mass was preventing, with the old rate, a too high solar Fe abundance. With this prescription for Fe in SNe Ia, the new rate produces a slightly low solar Fe, as a consequence of the differences between the old and new rate. Therefore, we adopted here, for the sake of homogeneity with the other galactic models presented here, the canonical $0.7M_{\odot}$ of Fe per SN (Nomoto et al. 1997) which, by the way, represents an even better average for the Fe mass. In fact, the spread found in the Fe among Type Ia SNe is as large as $0.1-1.1M_{\odot}$ (Cappellaro et al. 1997). By doing that, the age-metallicity relation, obtained by means of the new rate, is very similar to the old one. However, the solar Fe abundance obtained with the new rate and this prescription is still lower than the old one and in better agreement with the latest solar abundance determination by Asplund et al. (2005) (see Figure 4, where the theoretical solar abundance corresponds to the value at a time 9.5 Gyr, having assumed a galactic age of 14 Gyr).

In Figure 5 we show the same models of Figure 4 showing the [O/Fe] versus [Fe/H] relation. In this case, the [O/Fe] ratio obtained by means of the new rate is similar to the one in the case with the old rate for very low [Fe/H], but for [Fe/H] > -2.0 it decreases faster. The maximum difference between the two curves occurs at [Fe/H] ~ -1.0 dex and is roughly 0.2 dex. This is the consequence of the larger number of Type Ia SNe at early times obtained with the DTD of MVP06 which lowers the [O/Fe] ratio at a lower [Fe/H]. In Figure 5 we show also the data compiled by François et al. (2004). The fit to the data is not the best and the reason is that here, for purposes of homogeneity with the other galactic models, we do not adopt the empirical yields suggested

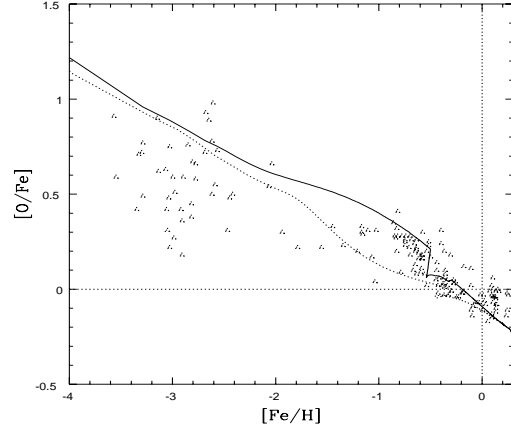


Figure 5. The computed [O/Fe] versus [Fe/H] relations for the same cases of Figure 4 (dotted line, MVP06 formulation, continuous line, MR01 formulation). The abundances of all models are normalized to the latest solar values of Asplund et al. (2005). The data are from the compilation of François et al. (2004). The horizontal and vertical lines represent the solar values.

by François et al. (2004) to best fit the data. In particular, the main difference is in the oxygen yields which here are those from Woosley & Weaver (1995) for solar chemical composition, whereas François et al. (2004) adopted those as functions of the metallicity for the best fit. The best model of François et al. (2004) is shown for comparison in Figure 6. This model differs from the others in the oxygen yields and in the stellar lifetimes which are those of Maeder & Meynet (1989). In Figure 6, we also plot the best model of François et al. when the MVP06 rate is assumed. As for the models of Figure 5 we can see that the main difference is the fast decrease of the [O/Fe] ratio for [Fe/H] > -2.0 dex. As it is evident from an inspection of Figures 5 and 6, both formulations of the Type Ia SN rate can fit the data, although the old one produces a better agreement with the data than the new one. It is worth noting that in the DTD of MR01 the percentage of systems exploding within 10^8 years is $\sim 13\%$, whereas in the new DTD is $\sim 50\%$. Our results indicate that perhaps this fraction is too high. On the other hand, the results of MVP06 indicates that this percentage can be as low as 35-40 % and still produce a good agreement with the radio data.

4.2 Ellipticals

In Figure 7 we show the computed Type Ia SN rates for a typical elliptical of $10^{11}M_{\odot}$ of initial luminous mass for the old and new formulations. The final stellar mass after the galactic wind, for this model, is $M_{*} = 3.5 \cdot 10^{10}M_{\odot}$ and the blue luminosity is $L_B = 4 \cdot 10^9 L_{B\odot}$. Note the very high values of the rates at early times, due to the very high star formation rate during the formation of the spheroids ($\sim 1000M_{\odot}yr^{-1}$), obtained by our model.

In the case of ellipticals, as we can see from Figure 7, it is possible to obtain almost the same present time Type Ia SN rate as in the old formulation (~ 0.04 SNe $(100yr)^{-1}$ in agreement with Cappellaro et al. (1999) observed rate), only

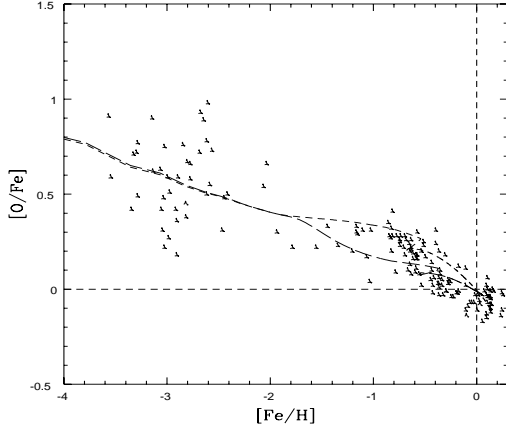


Figure 6. The computed $[O/Fe]$ versus $[Fe/H]$ relations for the best model of François et al. (2004) (short-dashed line); this particular model differs from the models of Figure 5 for the yields of oxygen in massive stars but the difference does not produce noticeable differences. More important is the difference in the stellar lifetimes which are those of Maeder & Meynet (1989), whereas in the models of Figure 5 and in all the models of this paper are from Padovani & Matteucci (1993). Here we show also the results of the best model of François et al. (2004) with the MVP06 rate (long-dashed curve). Also in this case the mass of Fe from each Type Ia SN was assumed to be $0.70M_{\odot}$ in analogy of what we did for the dotted model of Fig.5 (see text). The abundances of all models are normalized to the latest solar values of Asplund et al. (2005). The data are from the compilation of François et al. (2004). The horizontal and vertical lines represent the solar values.

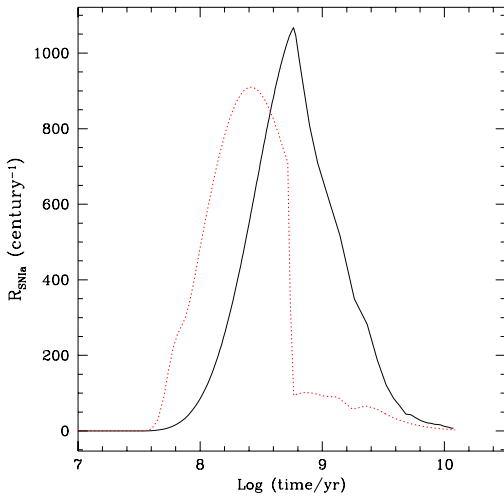


Figure 7. The computed Type Ia SN rate in the old and new formulation for a typical elliptical galaxy of $10^{11}M_{\odot}$ of initial luminous mass. The solid line is the SN Ia rate as obtained with the old formulation and the $A=0.18$. The dotted line represents the new rate computed with the DTD of MVP06 and $A=0.0045$. In both cases the adopted IMF is the Salpeter one.

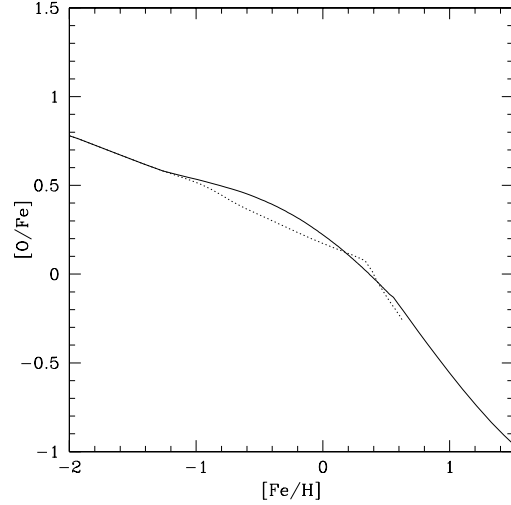


Figure 8. The computed $[O/Fe]$ vs. $[Fe/H]$ in the framework of the old (MR01) and new (MVP06) formulation for the Type Ia SN rate for a typical elliptical of $10^{11}M_{\odot}$ of luminous mass. The solid line is the relation obtained with the old formulation of MR01 with $A=0.18$ for a Salpeter (1955) IMF (see Pipino & Matteucci 2004), whereas the dotted one is the relation obtained with the new formulation, the Salpeter IMF and $A=0.0045$.

by changing the value of the A parameter, which is $A=0.18$ in the old formulation and $A=0.0045$ in the new one.

The new rate presents a higher number of SNe Ia at very early times but at late times coincides exactly with old one. In the case of an elliptical galaxy, in fact, the SFR proceeds like in a burst and for the majority of the cosmic time the galaxy is evolving passively. This is why there is not a great difference between the two rates at late times.

In Figure 8 we present the $[O/Fe]$ versus $[Fe/H]$ for the two cases: the old model of Pipino & Matteucci (2004) and the model with the new Type Ia rate. In this figure we can see the effect of the new rate on the $[O/Fe]$ vs. $[Fe/H]$ relation computed for the gas in a typical elliptical galaxy. In analogy with the Milky Way, the differences among the models with the new and old rate consist in a faster decrease of the $[O/Fe]$ ratio for $[Fe/H] > -1.0$ in the model with the new rate, due to the peak in the SNe Ia obtained with the MVP06 DTD. The fact that in ellipticals the difference in the $[O/Fe]$ ratio appears for $[Fe/H] > -1.0$ dex, whereas in the Milky Way it appears for $[Fe/H] > -2.0$ dex is due to the more efficient star formation in ellipticals which allows the gas to reach a high metallicity in a very short time.

Again, like for the case of the Milky Way we can conclude that the new formulation of the Type Ia SN rate leads to a higher Type Ia SN rate at early times and to a faster decrease of this rate at late times, but it does not affect substantially the galactic chemical evolution. It is worth noting that in the Pipino & Matteucci (2004) model the Fe mass produced by each SN Ia was assumed to be $0.7M_{\odot}$ and we did not change this value in the new formulation. The only noticeable difference between the new and old model is the maximum $[Fe/H]$ reached in the gas. In the new model is $[Fe/H]=+0.6$ dex, whereas in the old one is $[Fe/H] > +1.0$ dex. This fact does not have implications for the $[Fe/H]$ in the stars in ellipticals but only for the amount of Fe ejected

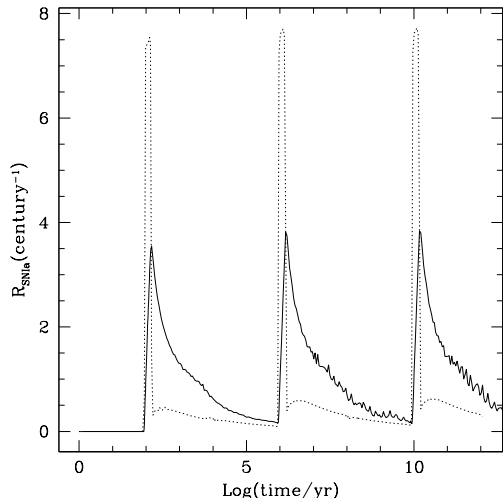


Figure 9. The computed Type Ia SN rate (multiplied by 10^5) as a function of cosmic time for a dwarf irregular galaxy with 3 bursts of star formation and efficiency of star formation $\nu = 0.1 \text{ Gyr}^{-1}$ with the new (dotted line) and old (continuous line) formulation. In the old formulation $A=0.09$, whereas in the new one is $A=0.0037$.

by ellipticals in the intracluster medium (ICM), as we will see in paragraph 5.4.

4.3 Dwarf irregulars

In Figure 9 we show the Type Ia SN rate for a typical dwarf starbursting irregular galaxy of luminous mass $10^8 M_\odot$. The old and new rates are compared for an euristic case with three starbursts of 0.2 Gyr duration and occurring at 2, 6 and 10 Gyr, respectively. The star formation efficiency is chosen to be $\nu = 0.1 \text{ Gyr}^{-1}$ in each burst.

As one can see from Figure 9, the main difference between the new and the old formulation of the Type Ia SN rate for a starburst regime consists in a larger amount of SNe Ia at the beginning of each starburst and in a lower amount of SNe in the interburst periods. The present time Type Ia SN rates in the two cases are similar and this is obtained by adopting $A=0.0037$ for the MVP06 case and $A=0.09$ for the MR01 case. The present time rates are: $3.4 \cdot 10^{-6} \text{ SNe } (100 \text{ yr})^{-1}$ for the MVP06 case and $2.8 \cdot 10^{-6} \text{ SNe } (100 \text{ yr})^{-1}$ for the MR01 case. These are very low values because we considered an euristic case with very few bursts and very low star formation efficiency.

Finally, in Figure 10 we show the calculated $[\text{O}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ for the new and old Type Ia SN rates. As one can see the behaviour of the $[\text{O}/\text{Fe}]$ ratio is similar in the two cases with the saw-tooth behaviour typical of the star burst regime of star formation, but the case with the new rate produces higher $[\text{O}/\text{Fe}]$ ratios (by ~ 0.2 dex) relative to the case with the old rate, especially after the first burst episode. The reason is that there are much less Type Ia SNe during the interburst phases than in the old formulation, and this contributes to keep higher the $[\text{O}/\text{Fe}]$ ratio. Therefore, with the new rate of Type Ia SNe dwarf starburst galaxies (with very few bursts) are found to have higher $[\alpha/\text{Fe}]$ ratios than with the old models. For an increasing number of bursts mimick-

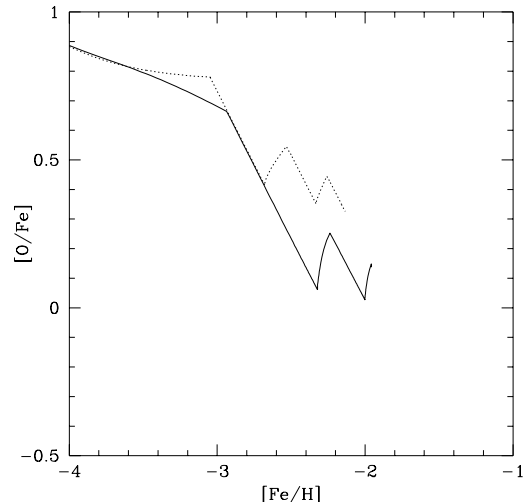


Figure 10. The computed $[\text{O}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ for a dwarf irregular galaxy with 3 bursts of star formation. The parameters of the models are the same as in Figure 9. The continuous line represents the model with the old formulation of the Type Ia SN rate of MR01 whereas the dotted line represents the model with the new rate (MVP06).

ing a continuous star formation, the differences between the $[\text{O}/\text{Fe}]$ ratios tend to disappear. As in all the previous cases, also here the final $[\text{Fe}/\text{H}]$ value reached in the gas is slightly lower for the new formulation of the Type Ia SN rate.

4.4 Chemical enrichment of the ICM

In this section we explore the effects of the new Type Ia SN rate on the chemical enrichment of the intracluster medium (ICM). Pipino et al. (2002) computed the contributions of the elliptical and S0 galaxies to the Fe abundance in clusters. Their method was based on the first paper of this series by Matteucci & Vettolani (1988) where the contribution to Fe and other heavy elements was, for the first time, computed by integrating the contribution from each galaxy on a Schechter (1976) luminosity function. The main assumptions are the contributions from each galaxy that only E and S0 galaxies contribute to the chemical enrichment of the ICM and that all the Fe produced by Type Ia SNe is lost into the ICM, either by galactic winds or ram pressure stripping. The main results of Matteucci & Vettolani (1988) were: the Fe content of both rich and poor clusters can be well reproduced whereas the contribution to the total cluster gas by galaxies is small, thus requiring that most of the gas has a primordial origin. This was confirmed by the fact that the estimated ratio between the mass of the ICM and the mass in galaxies in the Coma cluster is $M_{\text{ICM}}/M_{\text{Gal}} = 5.45$ (for $h = 70$, White et al. 1993). After this first paper, other studies concluded that the Type Ia SN rate should have been much higher in the past to explain the Fe in clusters (Ciotti et al. 1991; Renzini, 2004). Pipino et al. (2002) confirmed these results and calculated in detail when the Fe is ejected into the ICM by stellar winds, as well as considered the temporal evolution of the cluster luminosity function. They adopted models for elliptical galaxies very similar to that described before. In Figure 11 we show the abundance of Fe

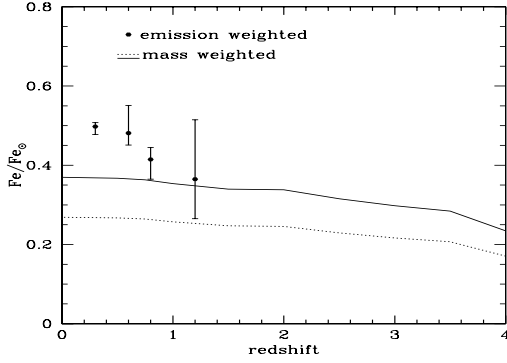


Figure 11. The calculated Fe/Fe_{\odot} in the ICM of a rich cluster (e.g. Coma) as a consequence of Fe mass loss by E and S0 galaxies, as a function of redshift. The adopted solar abundance, both in the models and data, is the one by Asplund et al. (2005). The model Universe assumed here implies $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$, and redshift of galaxy formation $z_f = 5.0$. The data (emission-weighted) are from Tozzi et al. (2003) and refer to rich galaxy clusters.

relative to the solar one produced by galaxies and ejected into the ICM of a rich cluster as a function of redshift, both in the case of the MR01 rate for Type Ia SNe and for the new rate. The chemical evolution model for ellipticals is that described in sects. 3.2 and 4.2. As expected, the difference in the behaviour of the temporal growth of the Fe abundance in the two cases is negligible. We find only a slightly lower Fe mass for the new rate. The reason for this can be found in the fact that with the new Type Ia SN rate, a larger Fe fraction is locked in stars relative to the old rate and therefore the amount of Fe which is ejected into the ICM is lower. In particular, the Fe mass in the ICM in the case of the new Type Ia SN rate is $\sim 30\%$ lower than in the case with the MR01 rate. In order to estimate the Fe abundance in the ICM in Figure 11 we have divided the total mass of Fe present in the ICM at any time by the total mass of gas in the cluster. For the case of a rich cluster like Coma, the amount of gas is $M_{ICM} = 1.5 \cdot 10^{14} M_{\odot}$. In conclusion, Figure 11 shows that in both cases the Fe in the ICM is not strongly evolving as a function of time (see also Scannapieco & Bildsten, 2005), and that galactic models with the new rate produce tend to produce too little Fe in the ICM. This again suggests that less Type Ia SNe at early times than in the DTD of MVP06 would improve the agreement with observations, as we concluded for the Milky Way. However, it is worth noting that the comparison between data and models in Figure 11 is only indicative since the models represent the mass-weighted Fe abundance, whereas the data represent the emission-weighted Fe abundances. These latter favor the central cluster regions where the Fe abundance is higher. In any case, the increasing Fe trend between redshift $z=1$ and $z=0$ seems to be confirmed by more recent data by Balestra et al. (2006). If this effect is real, then we should find some other Fe sources in the ICM acting at relatively recent times.

5 SUMMARY

In this paper we have tested a new formulation for the Type Ia SN rate in galaxies of different morphological type. The new formulation of the SN Ia rate is based on an empirical rate derived by MVP06 in order to reproduce various observational constraints relative to Type Ia SN rates and in particular the Type Ia rates versus radio flux in radio galaxies. It is suggested that $\sim 50\%$ of all SNe Ia should explode soon after the beginning of star formation and should therefore originate from stars with $M > 5M_{\odot}$, whereas the other half should originate from less massive progenitors. In the framework of the single degenerate model, such a bimodal distribution of the Type Ia SNe could be explained if the binary systems with a unitary mass ratio ($M_1/M_2 = 1$) are favored in the mass range $5-8M_{\odot}$, whereas for masses $< 5M_{\odot}$ the favored systems should have the mass of the primary much larger than the mass of the secondary. We included the suggested new rate in detailed models of chemical evolution of galaxies of different morphological type: the Milky Way, ellipticals and dwarf starburst galaxies. In general, we found an earlier and broader peak for the Type Ia SNe in any type of galaxy. It is worth noting that a DTD function with systems exploding after 30-40 Myr had already been adopted by GR83 and MR01, the only difference with the new DTD being the lower number of systems exploding at early times. In particular, in these formulations the fraction, relative to the total number, of Type Ia SNe exploding inside the first 0.1 Gyr since the beginning of star formation is $\sim 13\%$, to be compared with $\sim 50\%$ of MVP06.

We find that a spiral galaxy like the Milky Way should have a peak in the Type Ia rate before 1 Gyr from the beginning of star formation. This implies that Type Ia SNe can pollute the ISM already during the halo phase, thus producing a faster decrease of the $[O/Fe]$ ratio versus $[Fe/H]$ marginally in agreement with observational data. To this purpose, we should not forget that the MVP06 rate is an empirical one and the fraction of fast Type Ia SNe can be as low as 35-40% and still produce a good fit to the radio data. Our results suggest that less than 50% prompt Type Ia SNe would fit better the $[O/Fe]$ vs $[Fe/H]$ relation in the Milky Way, in agreement with all the previous results (Matteucci & Greggio, 1986; Chiappini et al., 2001; François et al. 2004.).

For ellipticals the differences are less noticeable since we assume that elliptical galaxies, especially the massive ones, have evolved very fast and at a very high redshift. The differences produced in the $[O/Fe]$ ratio in this case are negligible.

The same situation is true for dwarf starbursting objects where the main effect is a larger number of Type Ia SNe at the early stages of each burst and less SNe in the interburst phases, during which only Fe is produced. In this case, the effect of the new rate on the computed $[O/Fe]$ versus $[Fe/H]$ relation is larger, due to the high number of fast SNe Ia in each burst and the reduced number of them in the interburst phases. As a consequence of this, the $[\alpha/Fe]$ ratios in galaxies with a small number of bursts tend to be always oversolar.

We have also checked the effect of the new Type Ia SN rate on the chemical enrichment of the ICM: the behaviour of the Fe abundance as a function of cosmic time does not change but less Fe mass is ejected in total into the ICM relative to previous models (roughly 30% less). This is due to

the fact that the larger amount of Fe produced at early times is going to be locked into stars, thus lowering the fraction of Fe which will be ejected into the ICM. This again suggests a fraction of prompt Type Ia SNe lower than 50%.

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